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Lowering the pressure in district heating and cooling networks by alternating the connection of the expansion vessel

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ABSTRACT

Low-temperature district heating and cooling networks, operated at water temperatures below 20 °C, substitute fossil-based heating systems with environmental heat or waste heat from industrial processes and additionally provide a source of direct cooling during the warmer months. These networks have the potential to reduce carbon emissions and are a key future technology in the strategy to combat climate change. However, large initial investments limit the diffusion of such networks. A large fraction of those investments, apart from trenching, goes to piping. Piping costs are highly dependent on pipe diameter, material and pressure rating. In this work, we focus on reducing costs by reducing the pressure in the system; thus allowing a reduced pressure rating. To reduce the maximum pressure in a hydraulic system, we present a novel technique based on alternating the connection of the expansion vessel. We explain our concept in a lab experiment and subsequently apply our method to the large-scale network at ETH Zurich, Switzerland. At ETH Zurich, we predict a pressure reduction of 8% from 6 to 5.5 bar. Lowering the pressure increases the economic viability and may thus promote the market dissemination of low-temperature district heating and cooling networks.

1. Introduction

Using sources of renewable energy to cover the heating and cooling demands of buildings can reduce CO_2 emissions and help achieve the targets outlined in the IPCC [1]. In Switzerland, the Energy Strategy 2050 defines the national climatic goals. The Swiss Competence Center for Energy Research (SCCER), launched in 2013, develops strategies to meet these targets. Within the subprogram SCCER Future Energy Efficient Buildings and Districts (SCCER FEEB&D) [2], CO_2 emissions (per m^2 energy reference area) from buildings aim to be reduced by a factor of three by 2035 (compared to 1990). District heating networks have proven to distribute heat efficiently and cost effectively. Since the end of the 19th century, temperatures of the heat-carrying medium, usually water, have been gradually reduced. Starting from steam with temperatures of up to 200 °C, temperatures of 50 °C–70 °C are now prevalent in district heating networks. Such systems are referred to as the 4th generation of district heating [3]. Reducing the network temperature further increases the number of exploitable environmental heat sources and, at the same time, satisfies the growing demand for cooling. Renewable district heating and cooling technologies are growing research topics [4–7]. In this work, we focus on district heating and cooling networks with temperatures below 20 °C and simply refer to them as “low-temperature networks”. In such networks, heat pumps are necessary to reach temperatures of 40 °C–60 °C for room heating and domestic hot water production, whereas cooling does usually not require additional energy input[1] and is often referred to as “free- and/or geo-cooling”. Low-temperature networks provide a means to replace fossil-based heating systems (e.g. gas or oil burners), by environmental heat sources (e.g. geothermal heat, lakes, rivers, groundwater) and by recovering waste heat from industrial processes. These networks have the potential to reduce carbon emissions and are a key future technology in the strategy to combat climate change. In Switzerland, seven already partially or totally realized district heating and cooling networks with temperatures below 20 °C are documented [8] and more are under construction.

Networks that offer both, heating and cooling, are most

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[1] Except air-conditioning with dehumidification. In this case, an additional chiller is needed to cool the water.

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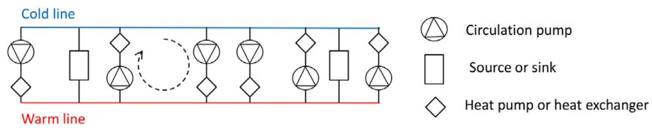

Fig. 1. Simplified scheme of a low-temperature network with various circulation pumps and sources/sinks. Circulation pumps draw water either from the warm line for heating or the cold line for cooling. If heating and cooling demand balance, hydraulic sub-cycles form, indicated by the circular arrow.

efficiently operated with active clients (buildings) equipped with their own circulation pumps, drawing water from either the warm line for heating or the cold line for cooling [9–13] (Fig. 1). The sources/sinks are passive without circulation pumps and the water flow across the sources/sinks results from the pressure difference between the warm and cold line, which is created by the circulation pumps of the active clients. If heating and cooling demand of two clients balance, a hydraulic sub-cycle will form (indicated by the dotted circular arrow in Fig. 1). This sub-cycle reduces the hydraulic power compared to a traditional hydraulic typology with a central circulation pump, where the water is always forced through the entire network. Moreover, in systems with distributed circulation pumps, heat pumps are operated more efficiently due to the elevated temperatures of the water, which is directly supplied from clients with cooling demand. Heating and cooling networks with distributed circulation pumps thus consume less electricity for circulation pumps and heat pumps compared to systems with a central circulation pump.

Despite the increased energy efficiency of systems with distributed circulation pumps, such networks are challenging to control, because of pump-pump interactions and complex pressure dynamics. Pump-pump interactions cause volume flow variations in the system. This is particularly critical in winter, when network temperatures are low and a decrease of volume flow through the heat pump decreases the outflow-temperature of the heat pump, initiating local freezing (cold spots) and causing damage to heat exchanger of the evaporator. Furthermore, if the pressure at the suction side of a circulation pump falls below evaporation pressure, cavitation may occur. To avoid cavitation, the system pressure is typically increased to a level that guarantees cavitation-free-operation for all operational states. This system pressure is often unnecessarily high and requires a large pressure resistance of the pipes.

This paper presents a method to decrease pressure in low-temperature networks by alternating the connection position of the expansion vessel while eliminating the risk of cavitation. In addition, the lower pressure saves piping costs, which is a major fraction of the total investments [14]. For example, a PE100 pipe of diameter 560 mm with a pressure resistance of up to 16 bar (pressure class PN16) costs 647 USD m^{-1} (personal communication Fernando Petrig, Lauber IWISA, Switzerland), whereas the same pipe with a pressure resistance of up to 10 bar (PN10) costs 454 USD m^{-1}, corresponding to a cost reduction of 30%.[2]

In Switzerland, three low-temperature networks suitable for applying our method are in operation and documented [8]: (i) The network of Suurstoffi district, Rotkreuz, (ii) the network Friesenberg of Familiengenossenschaft Zürich and (iii) the network of Campus Hönggerberg, ETH Zurich (ETHZ). The network of ETHZ is presented as a case study in section 3.1. All three networks are equipped with distributed circulation pumps drawing water from either the warm or the cold line. In general, our method is not restricted to low-temperature networks but applies to arbitrary hydraulic systems in which the volume flow changes direction (see also section 4.1). So far, however, this condition was only identified in low-temperature networks.

In this work, our concept of switching the connection of the expansion vessel is first tested experimentally. The findings are then applied to data collected from a large-scale low-temperature network located at ETH Zurich, Switzerland. For the implementation of the new concept, we suggest a mechanical, self-operating valve. We then discuss the findings with regard to cost reduction as well as energy saving potential and compare against other solutions.

2. Material and methods

2.1. The NODES lab

The NODES (“New Opportunities for Decentralised Energy Systems”)-Lab (Figs. 2 and 3a) is a low-temperature network on a laboratory scale. The construction of the NODES lab was motivated by the growing number of district heating networks in Switzerland using water below 20 °C as heat carrier.

The NODES lab is operated in two modes, (i) with an active source, equipped with a central circulation pump, and passive, valve-controlled clients, or (ii) with active clients, each equipped with a distributed circulation pump, and a passive source. In this work, we use mode (ii) to illustrate and validate our concept of a variable connection of the expansion vessel.

2.2. The low-temperature network of ETHZ

The hydraulics of the low-temperature network of ETHZ, Campus Hoenggerberg (Fig. 3b), are, in principle, similar to the hydraulics of the NODES lab (Fig. 3a) consisting of a warm and a cold line, various active clients and passive sources (geothermal borehole fields in the case of ETHZ). As in the NODES lab, the circulation pumps draw water either from the warm or from the cold line, depending on the heating and cooling demand. However, the size of the ETHZ network is much larger than the NODES lab. Warm and cold lines in the NODES lab are approximately 20 m long, whereas they are approximately 900 m long at ETHZ. Pipe diameters are 5 cm (NODES) and 54 cm (ETHZ) and volume flows are of the order 1 $m^3 h^{-1}$ (NODES) and 200 $m^3 h^{-1}$ (ETHZ). The method presented in this work, however, is independent of scale and thus illustrates an example of how concepts developed at lab scale

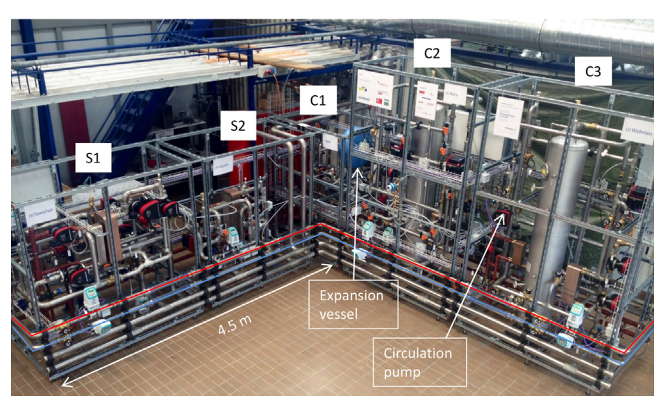

Fig. 2. NODES lab, a district heating and cooling network at laboratory scale. The warm (red) and the cold (blue) line form two loops around the laboratory. Three clients (C1, C2 and C3) and two sources (S1 and S2) draw water from either the warm or the cold line. The expansion vessel is connected either the cold or the warm line.

[2] Exchange rate (6 March 2018): 1 CHF = 1.06374 USD.

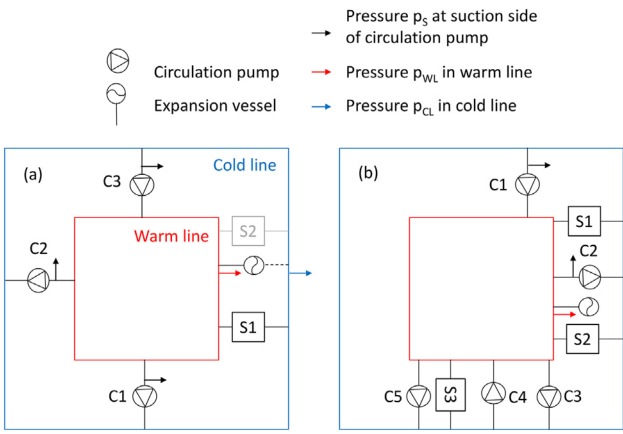

Fig. 3. Schematic of the hydraulics of (a) the NODES lab and (b) the ETHZ network. Clients C1 to C5 draw water from either the warm or the cold line. The sources S1, S2 and S3 are passive without circulation pumps. Pressure sensors are positioned in the warm and cold lines as well as at the suction sides of the circulation pumps. The expansion vessel is connected to either the warm or cold line in the NODES lab, indicated by the dashed line in (a), but is fixed to the warm line in the ETHZ network (b).

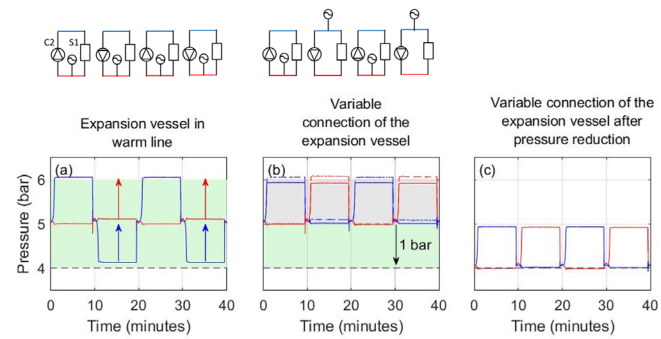

Fig. 4. Effect of a variable connection of the expansion vessel on the pressures in the warm and cold line. a, Pressures in the warm (red) and cold (blue) line when the expansion vessel is fixed to the warm line (indicated by the schematic above the panel). The green shading indicates the maximum and minimum pressure with a fixed expansion vessel, where the lower boundary of the green line represents the cavitation threshold. **b,** Same as (a) but with an expansion vessel that switches between the warm and cold line (indicated by the schematic above the panel). The grey shading indicates the maximum and minimum pressure with a variable expansion vessel. The dashed lines are calculated from (a) using the method described in the text. The black downward arrow indicates the possible pressure reduction of 1 bar **c,** Same a (b), but after a pressure reduction of 1 bar.

directly transfer to large-scale systems.

2.3. The position of the expansion vessel

The primary function of the expansion vessel in a hydraulic network is to absorb volume variations of the fluid caused by temperature changes. This avoids pipe damage caused by too large or too low pressures. Secondly, the expansion vessel is used to prevent cavitation in circulation pumps. Cavitation is caused by evaporation of fluid when the local pressure falls below evaporation pressure. The subsequent formation and implosion of gas bubbles induce pressure waves that damage circulation pumps. By connecting the expansion vessel to the suction side of the circulation pump, a sufficiently large pressure to avoid cavitation is guaranteed. In low-temperature networks with various circulation pumps the connection point of the expansion vessel is not well defined. The best practice is to fix the expansion vessel to an arbitrary point in the network and to increase the set pressure of the expansion vessel to a level that guarantees cavitation-free-operation for all operational states. In the following sections, we argue that a variable connection of the expansion vessel is an efficient solution to avoid cavitation at the lowest possible system pressure.

2.4. Effect of a variable connection of the expansion vessel on the system pressure

In Fig. 4, we show a simple measurement carried out at the NODES lab illustrating the effect of a variable expansion vessel during heating and cooling operation. In Fig. 4a, the expansion vessel is fixed to the warm line. Client C2 (Fig. 3a) alternatingly draws water from the warm and cold line switching every 10 min. The return flow passes through S1 and no water passes through clients C1 and C3 nor S2. A simplified hydraulic scheme of the situation is also shown above Fig. 4a. During the experiment, the pressure of the cold line varies between 4 and 6 bar, whereas the pressure of the warm line is kept constant at 5 bar by the expansion vessel. In this experiment, a pressure of 4 bar represents the cavitation threshold and is indicated by the dashed horizontal line (Fig. 4). In reality, however, the cavitation threshold is typically between 0.5 bar and 1 bar. In Fig. 4b, the same experiment is repeated with a variable connection of the expansion vessel. In this case, the expansion vessel is always connected to the line of lower pressure and thus alternates between the warm and cold line (see schematic above Fig. 4b). From minutes 0 to 10 and 20 to 30, the line of lower pressure is the warm line and system pressures are identical to Fig. 4a for the same time intervals. However, from minutes 10 to 20 and 30 to 40, the connection of the expansion vessel switches to the cold line as water is drawn from the cold line. Hence, the cold line is kept constant at 5 bar and the pressure in the warm line increases to 6 bar. Fig. 4b shows that there is a gap between the lowest pressure of the system and the minimum pressure to avoid cavitation; this allows the system pressure to be reduced. In Fig. 4c the system pressure of Fig. 4b is reduced by 1 bar.

2.5. Calculation of the system pressure with a variable connection of the expansion vessel

The pressures in a system with a variable connection configuration of the expansion vessel are calculated from the pressures experienced in a fixed connection configuration using the following procedure:

1. Measure the pressure at the current connection of the expansion vessel (point 1, the warm line in Fig. 4) and the alternative connection of the expansion vessel (point 2, the cold line in Fig. 4).
2. Determine the times when the pressure at point 2 is less than the pressure at point 1 (the time intervals from minutes 10 to 20 and from 30 to 40 in Fig. 4).
3. For those times, determine the pressure difference between point 1 and point 2 (approximately 1 bar in Fig. 4).
4. Add this pressure difference to *all* system pressures at these times. The resulting pressure situation (dashed lines in Fig. 4b) reflects the case of a variable expansion vessel alternating between point 1 and point 2.

The same method was used to estimate the effect of a variable connection of the expansion vessel at the network of ETHZ.

3. Results

3.1. Application to the network of ETHZ

The concept outlined in the previous section is applied to monitoring data of the low-temperature network of ETHZ, Campus Hoenggerberg, Switzerland (Fig. 3b). We examine a three-months-period from 1 May 2017 to 1 August 2017 and focus on clients C1 and C2 (Fig. 3b), as those exhibit the smallest pressures and are most critical for cavitation to occur. The expansion vessel is fixed to the warm line. Consequently, the pressure in the warm line is approximately constant at 4.6 bar, whereas the pressure in the cold line fluctuates (Fig. 5a). The suction side pressures in clients C1 and C2 are shown in Fig. 5b. The minimum pressure in the system is 1.5 bar and is observed on the suction side of client C2. The maximum pressure in the system is 6 bar and is observed in the cold line at periods of intense heating. The pressure variation in the system is 4.5 bar, indicated by the green shading in Fig. 5a and b and repeated in Fig. 5c and d.

The pressure achieved with a variable connection of the expansion vessel is shown in Fig. 5c and d. The pressure values were calculated from the measured pressures in Fig. 5a and Fig. 5b by applying the concept explained in section 2.5. As a consequence of a variable expansion vessel, pressure fluctuations are transferred from the warm line to the cold line (Fig. 5a, c) and the pressure minimum increases by 0.5 bar (Fig. 5c). The overall pressure in the system can thus be lowered by 0.5 bar (indicated by the downward arrow in Fig. 5d). Due to this pressure reduction, the maximum pressure decreases by 8% from 6 bar to 5.5 bar.

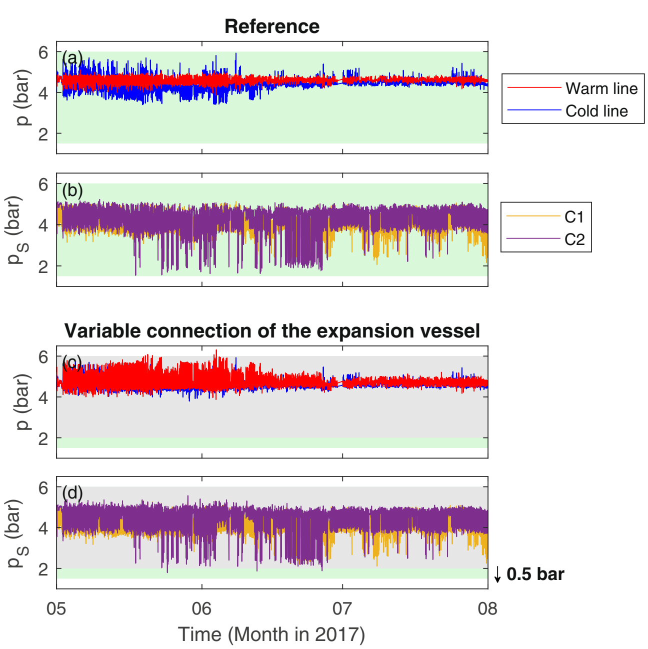

Fig. 5. Effect of a variable connection of the expansion vessel on the low-temperature network of ETHZ, Campus Hoenggerberg, Switzerland. **a,** Three-month time series of the pressures in the warm and cold line. The expansion vessel is fixed to the warm line. The green shading indicates the pressure range between the minimum and maximum pressure measured in (a,b) and is repeated in (c,d). **b,** Pressures at the suction sides of the circulation pumps in clients C1 and C2 for a fixed expansion vessel. **c,** Pressures of the warm and cold line, when the expansion vessel alternates between the warm and the cold line. The grey shading indicates the pressure range between the minimum and maximum pressure measured in (c,d) and is repeated in (d). **d,** As b, but for a variable connection of the expansion vessel. The downward arrow indicates a pressure reduction potential of 0.5 bar.

3.2. A new mechanical, self-operating valve for a variable connection of the expansion vessel

A new mechanical, self-operating valve was developed at the Lucerne University of Applied Sciences and Arts in order to easily alternate two expansion vessel connections (Fig. 6a). The valve is patent protected (Patent Nr. 01308/17) since 30 October 2017. The valve has three connection ports (Fig. 6a, b, c), one top port to the expansion vessel and two horizontal ports to the network lines. The pressure difference between the two horizontal ports exerts a force on the horizontal bolt (grey shading in Fig. 6b and c). This force directs the bolt towards the side of lower pressure, connecting the expansion vessel always to the line of lower pressure (green lines in Fig. 6b and c). As mechanical forces drive the valve, no external actuation nor any control algorithm is required. During the bolt movements, the network is connected to the expansion vessel at all times. This is an important condition to avoid overpressure in the system and to guarantee safe operation.

By combining identical valves (Fig. 6d), the number of connection points can be increased arbitrarily. Each added valve increases the number of connections points by one. In Fig. 6d, for example, the combination of four valves creates five connection points, of which only the point of lowest pressure is connected to the expansion vessel (green line in Fig. 6d).

4. Discussion

4.1. The "switching-sign" condition

Alternating the connection of the expansion vessel is effective, if the pressure difference between the connection points is reversing

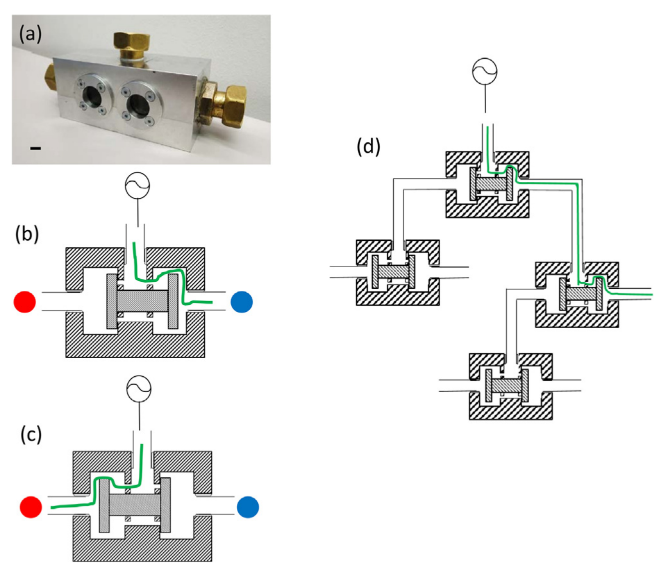

Fig. 6. The new mechanical, self-operating valve for a variable connection of the expansion vessel. a, Photograph of the valve. The two windows are for visual inspection. The scale bar corresponds to 1 cm **b,** Schematic cross-section of the valve. The top port connects to the expansion vessel and the two side ports connect to two different points in the network, typically to the warm line (left, marked by the red dot) and the cold line (right, marked by the blue dot). The bolt (continuous grey shading) moves horizontally such, that the side of lower pressure (here the blue port) is connected (green line) to the expansion vessel. The side of larger pressure (the red port) is disconnected from the expansion vessel. **c,** As (b), but for a reversed pressure situation. The expansion vessel is now connected to the left (red) port and disconnected from the right (blue) port. **d,** By combining valves, the number of possible connection points can be increased arbitrarily with n valves providing $n + 1$ connection points (here n = 4). Only the point of lowest pressure is connected to the expansion vessel (path marked by the green line).

("switching-sign") during operation. This condition is a feature of low-temperature networks with multiple distributed circulation pumps in the network.

In traditional district heating systems, with a central circulation pump, the volume flow is in one direction and the pressure always decreases along the flow direction. In this case, a single connection point of the expansion vessel is sufficient. Additional booster pumps used in large systems to take over part of the pressure losses in the supply and return lines do not change the situation, as they are operating in the same direction.

However, the "switching-sign"condition might also be fulfilled, when circulation pumps draw water from the same line but alternate in pumping speed. For example in Fig. 7a, the left circulation pump (marked green) draws water from the top line, whereas the right circulation pump is inactive with zero flow. Because the flow in the top line is from point 2 to point 1, the pressure at point 1 is lower than at point 2 (and point 3) and the expansion vessel ideally is connected to point 1. In Fig. 7b, the right circulation pump draws water from the top line, whereas the left circulation pump is inactive. The flow is now from point 2 to point 3 and the pressure at point 3 is lower than at point 2 (and point 1). The pressure difference between points 1 and 3 thus switches sign between Fig. 7a and b, fulfilling the condition for a variable expansion vessel. Because the bypass in Fig. 7 is in the centre between the two circulation pumps, and the pump activities are identical, a fixed expansion vessel at point 2 would have the same effect as a variable expansion between points 1 and 3. For arbitrary pump activities and bypass positions, however, a variable expansion is the safer and more effective solution.

4.2. Alternatives to a variable expansion

Switching the connection point of the expansion vessel changes the pressure level in the system at certain times. By varying the set pressure of the expansion vessel (and not the connection point), the same effect can be achieved. However, this requires a permanent monitoring of the suction side pressures in the system and a continuous adjustment of the set pressure of the expansion vessel. An automation system poses an operational risk by itself and is limited by the response time of the automated expansion vessel to sudden pressure variations.

A different approach is to change the hydraulic concept of the network. If large pressure drops, e.g. within the sources (Fig. 1, Fig. 3a and b) were compensated by additional circulation pumps placed at those sources, the pressure difference between the warm and cold line would tend to zero. A variable connection of the expansion vessel would then be obsolete. However, the control of the circulation pump to compensate for the pressure drop is still challenging and an additional bypass between the warm and the cold line is needed to compensate for imperfect control. A volume flow through the bypass mixes water from the warm and the cold line, inducing exergy losses, and should therefore be avoided.

4.3. A variable expansion has negligible effects on energy efficiency

A variable connection of the expansion vessel reduces the system pressure. Pressure affects fluid properties such as density, specific heat and viscosity, but only in a negligible way. For example, assuming a fluid temperature of 10 °C and a pressure reduction from 10 bar to 1 bar, changes in fluid density, specific heat and viscosity are all below 0.1% [15,16] and changes in the derived properties such as thermal energy storage capacity, thermal transfer coefficient and pressure losses in the pipe are of similar magnitude and thus negligible. Therefore, a pressure reduction has no noticeable effects on the thermodynamic properties that could influence energy efficiency.

4.4. The relevance of a variable expansion

When the system pressure is reduced, pipes with a lower pressure rating can be used. In the introduction, we calculated a price reduction of 30% per 6 bar of pressure reduction. A pressure reduction of 0.5 bar, as calculated for the network of ETHZ, thus corresponds to a theoretical cost reduction of 2.5% for piping. However, typical pressure classes for district heating piping have discrete maximum pressures of 6, 10, 16 and 25 bar. A pressure reduction of 0.5 bar is less than the pressure difference between the various pressure classes. Nevertheless, if the expected maximum pressure in the system is close to the upper end of one pressure class (e.g. 9 bar), a variable connection of the expansion vessel might provide the additional safety to justify the usage of the 10 bar class instead of the 16 bar class. This saves 30% of material costs and even more if welding costs are included. In this case, a variable connection of the expansion vessel has considerable potential to reduce capital investment.

In the future, we expect a growing number of low-temperature networks. We further expect those networks to merge, so that energy can be transferred not only between buildings, but also between individual networks to ensure security of supply. The complexity of the network will increase and operational states will be difficult to predict. However, the simple mechanism presented here to switch the connection point of the expansion vessel is independent of the network complexity and guarantees cavitation-free operation for all operational states at the smallest system pressure possible.

Moreover, when networks of at different geodetic altitude are connected, the pressure of the lower network increases, possibly reaching its pressure limits. The pressure reduction induced by a

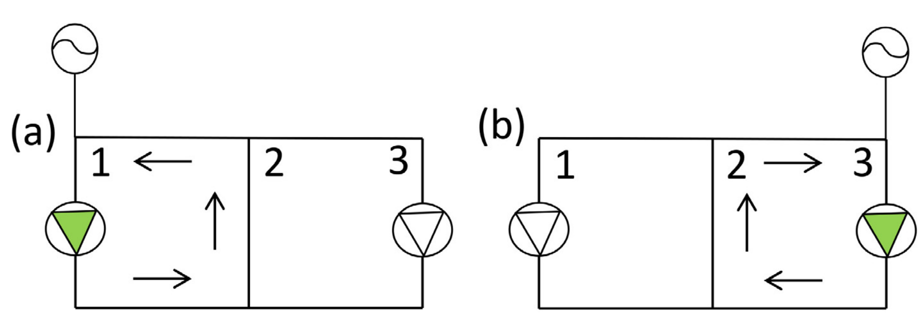

Fig. 7. Advantage of a variable expansion in a system, where both circulation pumps draw from the same line. a, The left circulation pump (green) is active, whereas the right circulation pump is inactive. Black arrows indicate the flow direction. Lines without arrows have zero flow. Points 1 and 3 are connection points of the expansion vessel. Point 2 is the connection point of the bypass to the top line. **b,** Same situation as in a, but with the right pump being active.

variable expansion vessel might then be an important mitigation measure to prevent expensive replacement of the piping.

5. Conclusions

We have presented a method to reduce the pressure in district heating and cooling networks by switching the connection point of the expansion vessel. The method is applicable, if the pressure difference between the connection points reverses during operation. The magnitude of the pressure reduction depends on the pressure difference between the connection points. The method was tested experimentally at the NODES lab, a laboratory-scale, low-temperature district heating and cooling network, and subsequently applied to monitored data from a large-scale network at ETH Zurich. At ETH Zurich, we predict a pressure reduction by 8% from 6 bar to 5.5 bar. For the practical realisation of a variable connection of the expansion vessel, we developed and presented a simple mechanical, self-operating valve. For low-temperature networks, particularly those with a large pressure difference between the warm and the cold line, a variable connection of the expansion vessel can significantly reduce piping costs, and thus reduce initial investment. In the future, as networks become more complex, switching the expansion vessel will ensure cavitation free operation for all operational status while maintaining the lowest possible system pressure.

Author contributions

Tobias Sommer: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Roles/Writing - original draft, Writing - review & editing. **Stefan Mennel:** Conceptualization, Funding acquisition, Project administration, Writing - review & editing. **Matthias Sulzer:** Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Writing - review & editing.

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